The Effects of Planets and Brown Dwarfs on Stellar Rotation and Mass-Loss

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ABSTRACT

We examine the effects of the engulfment of planets by giant stars on the evolution of late-type stars. We show that the rate at which dynamo-generated magnetic energy is being released exceeds 10% of the wind kinetic energy when the orbital angular momentum of the engulfed planet is more than ten times the angular momentum of the star as it leaves the main sequence. A significant enhancement in the mass-loss rate may be expected in this case, due to the formation of cool magnetic spots. We use the existing sample of extrasolar planets to estimate that at least 3.5% of the evolved solar-type stars will be significantly affected by the presence of planetary companions.

Subject headings: planetary systems – stars: evolution – stars: mass-loss – stars: magnetic fields – stars: statistics – stars: low mass, brown dwarfs

1. Introduction

Radial velocity surveys of nearby stars have been enormously successful in discovering extrasolar planets. These surveys have demonstrated that a significant fraction of the stars in the solar neighborhood have massive planets with orbital radii that are substantially smaller than Jupiter's (e.g. Marcy & Butler 2000; Udry et al. 2001; Butler 2001; Vogt et al. 2002). The engulfing of these planets by their parent stars is an inevitable outcome of stellar evolution (either directly or due to tidal interaction) in the red giant branch (RGB) or asymptotic giant branch (AGB) phase (e.g. Livio & Soker 1984; Siess & Livio 1999a,b). The capture of planetary-mass companions has been suggested to be the potential cause for the high rotational velocities ($V_{\rm rot} \sin i \gtrsim 10$ km s^{-1}) observed in some field red giants (Stefanik et al. 2001) and blue horizontal branch stars (e.g. Peterson et al. 1983; Soker & Harpaz 2000).

In the present work we examine specifically the effects of planet/brown dwarf "swallowing" on the rotation rates of and mass loss from giants. In particular, we estimate the expected statistics of influenced stars.

2. Rotation and Mass Loss in Evolved Late-Type Stars

When a star in the RGB or AGB phase engulfs a planet/brown dwarf the latter deposits its angular momentum into the giant's envelope. The resulting rotation frequency, as a fraction of the critical stellar rotation frequency $\omega_k \equiv (GM_*/R_*^3)^{\frac{1}{2}}$ (where M_*, R_* are the stellar mass and radius respectively) is given by

$$\frac{\omega}{\omega_k} \simeq 0.10 \left(\frac{M_c}{0.01 \text{ M}_\odot}\right) \left(\frac{M_{\rm env}}{\text{M}_\odot}\right)^{-1} \left(\frac{k_g^2}{0.1}\right)^{-1} \left(\frac{a}{R_*}\right)^{\frac{1}{2}} \quad . \tag{1}$$

Here M_c is the companion mass, $M_{\rm env}$ is the mass of the giant's envelope, $Mk_g^2R^2$ is the star's moment of inertia and a is the initial separation between the giant and the companion. Since stars like the Sun rotate only at a fraction of a percent of their critical rate (on the main sequence) and this fraction is further reduced (by conservation of angular momentum) to

$$\left(\frac{\omega}{\omega_k}\right)_{\rm AGB} \lesssim 0.1 \left(\frac{\omega}{\omega_k}\right)_{\rm MS} \left(\frac{R_{\rm MS}}{0.01 R_{\rm AGB}}\right)^{\frac{1}{2}} \quad , \tag{2}$$

as the stars ascend the RGB or AGB, we see from eq. (1) that even Jupiter-mass planets can have a very significant effect on the rotation rate of late-type stars. Even when the increase in central condensation is taken into account, typically, $(\omega/\omega_k)_{\rm AGB} \sim (0.01 - 0.1)(\omega/\omega_k)_{\rm MS}$ (e.g. Eriguchi et al. 1992).

The effects on mass loss rates are more difficult to estimate because they involve the processes of generation of magnetic activity (especially in spots) and mass loss via radiation pressure on molecules and dust, both of which are rather poorly understood. Nevertheless, it has been shown semi-quantitatively that the spiraling-in process of the companion inside the giant's envelope can result in a dynamo generation of a magnetic field (Regös & Tout 1995).

Here we shall adopt a simplified, more heuristic approach (similar to that of Soker & Harpaz 1992) to estimate at what rotation rates we can expect significant effects on mass loss. Dynamo-generated magnetic fields are limited by the requirement that the amplification timescale τ_a be of the order of the buoyant rise time of magnetic flux tubes (e.g. Parker 1979, §8.7). In a typical stellar $\alpha\omega$ dynamo the amplification timescale is given approximately by (e.g. Zeldovich, Ruzmaikin & Sokoloff 1983)

$$\tau_a \simeq \pi \left(\frac{2}{\alpha R_* k \nabla\omega} \right)^{\frac{1}{2}} \quad , \tag{3}$$

where $\alpha = \ell\omega_o/3$ is determined by convection (ℓ is the mixing length and ω_o the surface angular velocity), k is the wave number and $\nabla\omega$ is a measure of differential rotation. The critical wave number k_c below which dynamo waves are amplified is given by (ν_τ is the turbulent viscosity)

$$k_c^3 \simeq \alpha R_* \nabla\omega / 2\nu_\tau^2 \quad . \tag{4}$$

Adopting the same values as Zeldovich et al. (1983), $\nabla\omega = \omega_o/(0.3R_*)$, $\nu_\tau = \ell v_c/3$, where v_c is the convective velocity, and taking the wave number to be equal to the critical one, we find

$$\tau_a \simeq \frac{2\pi}{\omega_o} \left(\frac{v_c}{7\ell\omega_o} \right)^{\frac{1}{3}} \quad . \tag{5}$$

For typical AGB star parameters, $v_c \simeq 10$ km s^{-1}, $<\ell>\sim R_*/4$, the obtained average amplification time is of the order of $\tau_a \simeq 9\tau_{\rm rot}$, where $\tau_{\rm rot}$ is the rotation period. The local rise time of a flux tube is given approximately by (Parker 1979)

$$\tau_r \simeq \frac{\Lambda v_c}{V_A^2} = \frac{4\pi\rho\Lambda v_c}{B^2} \quad , \tag{6}$$

where V_A is the Alfven speed, B is the magnetic field strength, $\Lambda \sim r/2$ (where r is the radial distance from the center; e.g. Soker & Harpaz 1999) is the local scaleheight and ρ is the density. The density in the convective zone of an AGB star can be well approximated by (Soker 1992)

$$\rho(r) \simeq 2\times10^{-8} \left(\frac{M_{\rm env}}{0.1\ {\rm M}_\odot} \right) \left(\frac{R_*}{300\ {\rm R}_\odot} \right)^{-1} \left(\frac{r}{100\ {\rm R}_\odot} \right)^{-2} \ {\rm g\ cm}^{-3} \quad . \tag{7}$$

Equating the flux tube rise time τ_r to the regeneration and amplification time τ_a yields a value for the magnetic field

$$B \simeq 1.8 \left(\frac{M_*}{\mathrm{M}_\odot}\right)^{\frac{1}{3}} \left(\frac{R_*}{300\ \mathrm{R}_\odot}\right)^{-\frac{4}{3}} \left(\frac{M_{\mathrm{env}}}{0.1\ \mathrm{M}_\odot}\right)^{\frac{1}{2}} \left(\frac{v_c}{10\ \mathrm{km\ s}^{-1}}\right)^{\frac{1}{3}} \left(\frac{\omega_o/\omega_k}{10^{-3}}\right)^{\frac{2}{3}} \left(\frac{r}{100\ \mathrm{R}_\odot}\right)^{-\frac{1}{2}} \ \mathrm{G} \ . \tag{8}$$

Magnetic energy is thus being released at a rate

$$\begin{aligned} \dot{E}_B &= \frac{1}{\tau_a}\int \frac{B^2}{8\pi} 4\pi r^2 dr \\ &\simeq 10^{28} \left(\frac{M_{\mathrm{env}}}{0.1\ \mathrm{M}_\odot}\right) \left(\frac{v_c}{10\ \mathrm{km\ s}^{-1}}\right)^{\frac{1}{3}} \left(\frac{R_*}{300\ \mathrm{R}_\odot}\right)^{-\frac{7}{3}} \left(\frac{M_*}{\mathrm{M}_\odot}\right)^{\frac{4}{3}} \left(\frac{\omega_o/\omega_k}{10^{-3}}\right)^{\frac{8}{3}} \ \mathrm{erg\ s}^{-1} \ . \end{aligned} \tag{9}$$

The kinetic energy associated with the mass loss from an AGB star is of order

$$\dot{E}_{\mathrm{wind}} \simeq 3 \times 10^{31} \left(\frac{\dot{M}}{10^{-6}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}}\right) \left(\frac{V_w}{10\ \mathrm{km\ s}^{-1}}\right)^2 \ \mathrm{erg\ s}^{-1} \ , \tag{10}$$

where $\dot{M}$ is the mass-loss rate and V_w is the wind velocity. An examination of eqs. (9) and (10) reveals that for the companion to have an appreciable effect on mass loss (i.e. to have $\dot{E}_B > 0.1\dot{E}_{\mathrm{wind}}$) it must increase the angular momentum of the envelope (and thereby ω_o/ω_k) by an order of magnitude (or more). Consequently, in our estimate of the fraction of stars that are affected significantly by planetary companions, we shall adopt as the defining condition

$$J_p > 10 J_* \ , \tag{11}$$

where J_p is the orbital angular momentum of the planet, and J_* is the angular momentum of the star as it leaves the main sequence [eq. (2)]. Note that this is probably a reasonable criterion for the planet having a significant effect on stellar evolution even considering the uncertain nature of the effects on mass loss. In fact, given that the magnetic field in stellar spots can be $\sim 10^3$ times stronger than the average field (e.g. Priest 1987), condition (11) may be too stringent, since even a field lower by an order of magnitude than that given by eq. (8) will result in spots that are significantly cooler than their surroundings (magnetic pressure larger than the photospheric pressure).

3. Statistics on Importance of Planets

We define the following quantities

$$\begin{aligned} \nu &\equiv \log(a/AU) \\ \mu &\equiv \log(M/M_J) \end{aligned} \tag{12}$$

where a is the orbital separation, M is the minimum planetary mass, and M_J is Jupiter's mass. In Fig. 1 we show the known 75 planets (taken in January 2002 from the *Extrasolar Planets Encyclopaedia* compiled by J. Schneider, at http://www.obspm.fr/encycl/encycl.html) in the ν–μ plane. In planetary systems where more than one planet is known we mark the most massive planet by an asterisk, while the others are marked by the + sign. Several authors have attempted recently to obtain unbiased distributions of planets as a function of ν and μ (e.g. Lineweaver & Grether 2002; Mazeh & Zucker 2002; Tabachnik & Tremaine 2002; Armitage et al. 2002). In view of the uncertainties, we adopt the following simple form for the fraction of systems dN within a box $d\nu d\mu$ (for the parameter space indicated below)

$$dN = C(1 + \alpha\nu)(1 - \beta\mu)d\mu d\nu \quad , \tag{13}$$

for $-1.5 < \nu < 0.5$ and $\mu < 0.5\nu + 0.75$. Here C, α and β are parameters. This form is the same as the one used by Lineweaver & Grether (2002), who found (their figures 3 and 4) $\alpha \simeq 0.8$ and $\beta \simeq 0.8$. Using the well populated parallelogram (i.e. excluding areas in the $\nu - \mu$ plane with large gaps; see also Zucker & Mazeh 2002) marked by lines 1 to 4 on Figure 1, we estimate $\alpha \simeq 0.3$ and $\beta \simeq 0.5$. Examining in addition the results of Mazeh & Zucker (2002), Tabachnik & Tremaine (2002), and Armitage et al. (2002), and fitting where necessary their functional forms to ours, gives average values of $<\alpha>\simeq 0.6$ and $<\beta>\simeq 0.5$, which we shall now adopt.

The value of C can be determined for fixed values of α and β in the following way. From a sample of 1,200 stars discussed by Vogt et al. (2002; where more details can be found) 44 planets and 4 brown dwarfs have been detected. Hence 3.7% of the surveyed stars were found to have planets. The 75 known extrasolar planets (as of the end of January 2002) are distributed in 67 planetary systems. Using this ratio we find that the fraction of stars being detected to harbor planetary systems is $\sim$ 3.3%. If we examine the well populated area of Figure 1 (bounded by the four straight lines $\nu = 0.5$; $\mu = 0.5\nu + 0.75$; $\nu = -1.5$; and $\mu = 0.5\nu$), we find that out of the 67 planetary systems, 48 are inside this parallelogram. This corresponds to $\sim$ 2.4% of the stars having their massive planet within this region. Considering that the right side of this region is close to the detection limit (no planets are found near $\nu \simeq 0.4$ and $\mu \sim 0.3$), we take the detection fraction within this region to be $N_s \simeq 2.5\%$ of all stars. For stars with a metallicity above solar, [Fe/H] > 0, the detection fraction is $\sim$ 2.6 times higher than that for the entire sample (Vogt et al. 2002). Hence, in the same scaling-region the fraction is $N_s \simeq 6.5\%$. The large increase with metallicity in the probability of harboring a planet was studied by Gonzalez (1997) and Reid (2002). The latter author argues that most stars with a metallicity [Fe/H] > 0.3 have planets around them. We therefore take $N_s = 0.025$ for all stars and $N_s = 0.065$ for metal rich stars, and

find the value of C from the expression

$$N_s = C\int_{-1.5}^{0.5} d\nu \int_{0.5\nu}^{0.5\nu+0.75} d\mu(1+\alpha\nu)(1-\beta\mu) = \frac{C}{32}(48-24\alpha-6\beta-5\alpha\beta) = 0.9094C. \quad (14)$$

where the last equality was obtained by substituting the average values $\alpha = 0.6$ and $\beta = 0.5$.

In the previous section we derived as our condition for a significant effect on mass-loss from the parent star, $J_p > 10J_*$. We noted, however, that it is possible that even a lower angular momentum might play some role, especially since the star loses angular momentum as it evolves (Soker 2001). Soker further argues that planets of masses as low as $0.01M_J$ are sufficient to influence the mass loss *geometry* from AGB stars. An indirect hint that even a relatively slow rotation may influence the mass loss rate comes from the distribution of stars on the horizontal branch in globular clusters (GCs). D'Cruz et al. (1996) show that the distribution of stars on the horizontal branch in the HR diagram can be explained by variations in the mass loss rate on the RGB, by a factor which depends on the metallicity (ranging from 1.5 in metal rich GCs to $\gtrsim 5$ in metal poor GCs). We should note that red horizontal branch stars also rotate (Stefanik et al. 2001). However, using the results of Behr et al. (2000) for M13, Soker & Harpaz (2000) showed that the average angular momentum of the progenitors of hotter horizontal branch stars is larger than that of cooler ones. It is thought that rotation is the main factor that influences the mass loss rate variations (R. Rood, private communication, 2002), with the exception of very high mass loss rates which may result from interactions with stellar binary companions. Since main sequence stars in GCs are expected to rotate very slowly (since they have experienced a long period of angular momentum losses due to magnetic activity), if the rotation conjecture is correct, then very slow rotation is sufficient to influence mass loss on the RGB. Our condition, therefore, may be somewhat conservative.

The present angular momentum of the Sun is 1.7×10^{48}g cm^2 s^{-1}. A planet with a Jupiter mass at 1 AU from a solar type star has ~ 50 times the present angular momentum of the Sun. Taking as a typical value $J_* = J_\odot$, our condition in equation (11) reads $(M/M_J)(a/\ \mathrm{AU})^{1/2} \gtrsim 0.2$. For a more general form $J_p > \eta J_* = \eta J_\odot$, our condition reads

$$\mu + 0.5\nu \gtrsim \log(\eta/10) - 0.7 \equiv j_m \quad . \quad (15)$$

In addition, we limit the planet to $a < 2$ AU (or $\nu < 0.3$), in order for tidal forces to be able to bring it into the RGB or AGB star's envelope. These conditions are represented (for $\eta = 10$) as the two thick lines in Fig. 1. Planets to the left of and above these lines affect the evolution of their parent stars significantly (neglecting eccentric orbits of planets at larger orbital separations).

Not including the few systems above the line marked '2' in Fig. 1, the total fraction of planetary systems that are likely to significantly influence the evolution of the central star at late stages is therefore,

$$N(\text{total}) = C \int_{-1.5}^{0.3} d\nu \int_{j_m - 0.5\nu}^{0.5\nu + 0.75} d\mu (1 + \alpha\nu)(1 - \beta\mu) \quad . \tag{16}$$

Note that this integral is meanigful for $j_m < -0.7$. For $j_m > -0.7$ the thick diagonal line in Fig. 1 crosses the upper limit as given by line '2.' Performing this integral for $\alpha = 0.6$ and $\beta = 0.5$, and substituting for C from equation (14), we find

$$N(total) = N_s(0.4 - 1.2j_m + 0.3j_m^2) \quad . \tag{17}$$

Equation (17) shows that for our strong condition of $\eta = 10$, we find that more than 3.5% of all solar-type stars are significantly affected (in terms of rotation rate and mass loss) by planets or brown dwarf companions. This number increases to more than 9% for metal rich (above solar) stars. Relaxing the condition to $\eta = 1$, i.e. when the planet's orbital angular momentum equals the present one for the sun, increases the numbers to be $> 8\%$ and $> 21\%$ respectively. All of these numbers should probably be regarded as lower limits, since we have neglected the effects of planets at 2 AU$\lesssim a \lesssim$ 5 AU in eccentric orbits (which could also be pulled into the giant's envelope by tidal interaction; see also Debes & Sigurdsson 2002), and used only the minimum masses (as well as not having included the planets above line '2' in Fig. 1).

4. SUMMARY

We have shown that the swallowing of planetary or brown dwarf companions can have significant effects in the late stages of the evolution of late-type stars. Specifically, we considered rotation and mass loss. On the basis of the properties of the observed extrasolar planets, we estimated that $\sim$ 4–10% of the stars should experience enhanced mass loss due to the effects of planets.

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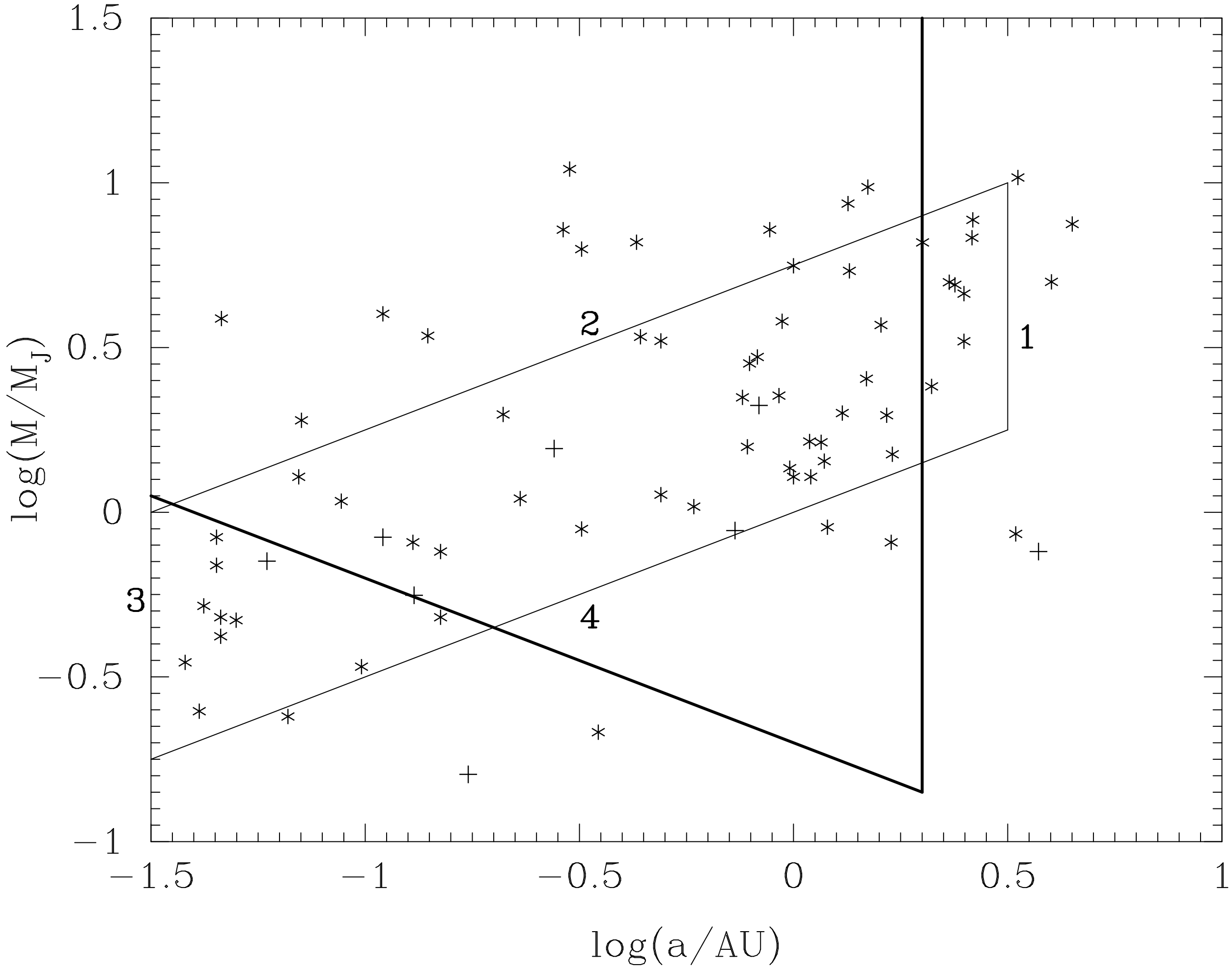

Fig. 1.— 75 known extrasolar planets are presented in the minimum-mass–semimajor-axis logarithmic plane. In planetary systems where more than one massive planet has been found, the most massive one is marked by *, while the others by +. The four lines marked 1 to 4 define the area used for our scaling of fraction of planets. The two thick lines represent our condition for a planet to significantly influence the mass loss rate of its parent star (see text).